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On the Unusual Depletions toward Sk 155 or What Are the Small Magellanic Cloud Dust Grains Made of?

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ABSTRACT

The dust in the Small Magellanic Cloud (SMC), an ideal analog of primordial galaxies at high redshifts, differs markedly from that in the Milky Way by exhibiting a steeply rising far-ultraviolet extinction curve, an absence of the 2175 Å extinction feature, and a local minimum at $\sim 12\,\mu$m in its infrared emission spectrum, suggesting the lack of ultrasmall carbonaceous grains (i.e. polycyclic aromatic hydrocarbon molecules) which are ubiquitously seen in the Milky Way. While current models for the SMC dust all rely heavily on silicates, recent observations of the SMC sightline toward Sk 155 indicated that Si and Mg are essentially undepleted and the depletions of Fe range from mild to severe, suggesting that metallic grains and/or iron oxides, instead of silicates, may dominate the SMC dust. However, in this *Letter* we apply the Kramers-Kronig relation to demonstrate that neither metallic grains nor iron oxides are capable of accounting for the observed extinction; silicates remain as an important contributor to the extinction, consistent with current models for the SMC dust.

Subject headings: dust, extinction — ISM: abundances – Magellanic Clouds – stars: individual (Sk 155)

1. Introduction

As a metal-poor (with a metallicity only ∼1/10 of that in the Milky Way; see Kurt & Dufour 1998) and gas-rich (with a dust-to-gas ratio over 10 times lower than in the Milky Way; see Bouchet et al. 1985) irregular dwarf galaxy, the Small Magellanic Cloud (SMC) is

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often considered as a local analog of primordial galaxies at high redshifts which must have formed at very low metallicity. Therefore, the dust in the SMC which differs substantially from that in the Milky Way (see Li & Draine 2002) allows us to probe the primordial conditions in more distant galaxies.

The SMC extinction curve displays a nearly linear rise with inverse wavelength and no detectable 2175 Å extinction bump (Lequeux et al. 1982; Cartledge et al. 2005), presumably due to the destruction of the carriers of the 2175Å hump by the intense ultraviolet (UV) radiation and shocks associated with star formation [an exception to this is the line of sight toward Sk 143 (AvZ 456) for which the extinction curve has a strong 2175Å hump (Lequeux et al. 1982; Cartledge et al. 2005). This sightline passes through the SMC wing, a region with much weaker star formation (Gordon & Clayton 1998)]. Although the precise nature of the carriers of the 2175Å hump remains unclear, it is generally believed to be due to the $\pi \rightarrow \pi^*$ transition of small aromatic carbonaceous (i.e. graphitic) grains, probably a cosmic mixture of polycyclic aromatic hydrocarbon (PAH) molecules (Li & Draine 2001). The overall infrared (IR) emission spectrum of the SMC peaks at $\lambda \sim 100\,\mu$m with a local minimum at $\lambda \sim 12\,\mu$m which is commonly believed to be emitted by PAHs (see Stanimirovic et al. 2000, Li & Draine 2002 and references therein).

The absence of the 2175 Å extinction bump and the very weak $12\,\mu$m emission in the SMC imply the lack of PAHs in the SMC.[1] The paucity of PAHs appears to be a general feature of metal-poor galaxies (e.g. see Madden 2000, Thuan et al. 1999, Houck et al. 2004, Engelbracht et al. 2005, Wu et al. 2006). A natural question one may ask is: are their large-size counterparts – carbon dust (either graphite or amorphous carbon) with radii larger than ~ 100 Å – also deficient in the SMC and low-metallicity galaxies, or more generally, what are the dust grains in the SMC (or metal-poor galaxies) made of?

Our knowledge about the SMC dust is mainly derived from the extinction curve. As early as 1983 when the ~ 3–$9\,\mu\mathrm{m}^{-1}$ UV extinction data were just available for the SMC thanks to the IUE satellite, Bromage & Nandy (1983) had already recognized "the conspicuous *absence* of normal *graphite* grains in the SMC". Subsequent models for the SMC dust all rely heavily on *silicates*, with a silicate to carbon mass ratio of ~ 5.5 (Rodrigues et al. 1997), ~ 2.5 (Zubko 1999), ~ 12 (Weingartner & Draine 2001), ~ 1.6 (Clayton et al. 2003), and ~ 12 (Cartledge et al. 2005). Pei (1992) even attributed the SMC extinction exclusively to silicates alone. However, based on an analysis of the HST/STIS interstellar absorption spectra of the SMC components, Welty et al. (2001) recently reported that the Si and Mg elements in the

[1] The PAH emission features have been detected locally – in the SMC B1 No. 1 quiescent molecular cloud (Reach et al. 2000), and in the N 66 star-forming region (Contursi et al. 2000).

interstellar cloud toward Sk 155 in the SMC appear to be essentially *undepleted*, imposing a serious *challenge* on all dust models for the SMC since they all require a substantial amount of silicates to account for the observed extinction.

It is the purpose of this *Letter* to examine the *unusual* depletions observed in the SMC sightline toward Sk 155. To this end, we investigate whether the depleted elements are sufficient to account for the observed extinction. Our approach, as described in §2, is based on the Kramers-Kronig (KK) dispersion relation (Purcell 1969) and is independent of any specific dust models.

2. Constraints from the Kramers-Kronig Relation

In 1926–1927, H.A. Kramers and R. Kronig independently demonstrated that the real (dispersive) and imaginary (absorptive) parts of the index of refraction are not independent, but are related to each other through a relation which is now known as the Kramers-Kronig (KK) dispersion relation. Applying this relation to the ISM, Purcell (1969) related the interstellar extinction integrated over wavelength to the total volume of grains in the ISM: $\int_0^\infty \tau_{\rm ext}(\lambda)/N_{\rm H}\,d\lambda = 3\pi^2 F\,V_{\rm dust}^{\rm tot}/{\rm H}$, where $\tau_{\rm ext}(\lambda)$ is the extinction optical depth at wavelength λ, $N_{\rm H}$ is the H column density, $V_{\rm dust}^{\rm tot}/{\rm H}$ is the total volume occupied by dust per H nucleon, and the dimensionless factor F is the orientationally-averaged polarizability relative to the polarizability of an equal-volume conducting sphere, which depends only upon the grain shape and the static (zero-frequency) dielectric constant ϵ_0 of the grain material (Purcell 1969).[2]

Very recently, we have applied this relation to examine whether porous dust could solve the so-called interstellar subsolar abundance "crisis" (Li 2005). Similarly, this approach can be applied to the unusual depletions seen along the Sk 155 sightline: if Si and Mg are indeed undepleted, would there be enough raw material to form the dust to account for the extinction observed for the SMC?

To make an economical use of the heavy elements, we consider fluffy dust with a "fluffiness" or "porosity" of P (i.e. the volume fraction of vacuum contained in a grain). Assuming that all heavy elements depleted from the gas phase have been locked up in dust which consists of N grain species, the *maximum* volume of dust per H nucleon can be es-

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[2]The static dielectric constants of the dust materials adopted in this *Letter* are: $\epsilon_0 \approx 10$ for amorphous olivine (Draine & Lee 1984), $\epsilon_0 \approx 9$ for MgO (Roessler & Huffman 1998), $\epsilon_0 \approx 28$ for FeO, $\epsilon_0 \approx 16$ for Fe_2O_3 (Steyer 1974), $\epsilon_0 \approx 23$ for Fe_3O_4 (Landolt & Börnstein Tables), and $\epsilon_0 \approx 6$ for amorphous carbon (J. Robertson 2005, private communication).

timated from $V_{\rm dust}^{\rm tot}/{\rm H} = \sum_{j=1}^{N}\sum_{\rm X} f_{{\rm X},j}\left([{\rm X/H}]_{\rm tot} - [{\rm X/H}]_{\rm gas}\right)\mu_{\rm X}/\left(1-P\right)\rho_j$, where $[{\rm X/H}]_{\rm tot}$ and $[{\rm X/H}]_{\rm gas}$ are respectively the total and gas abundance of element X relative to H (the amount of X contained in dust is therefore $[{\rm X/H}]_{\rm dust} = [{\rm X/H}]_{\rm tot} - [{\rm X/H}]_{\rm gas}$); $\mu_{\rm X}$ is the atomic weight of X; ρ_j is the mass density of dust species j (we take $\rho = 3.5$, 3.58, 5.7, 5.25, 5.18, 1.8, and $7.85\,{\rm g\,cm^{-3}}$ for amorphous olivine $MgFeSiO_4$, MgO, FeO, Fe_2O_3, Fe_3O_4, amorphous carbon, and pure iron grains, respectively); and $f_{{\rm X},j}$ is the fraction of element X locked up in dust species j. The first summation is over all possible dust species and the second one is over all condensible elements. Since $\tau_{\rm ext}(\lambda)$ is a positive number for all wavelengths, we can use the extinction observed over a *finite* wavelength range (say, from 912 Å to 1000μm) to place a lower bound on $F/\left(1-P\right)$: $f_{\rm obs}^{\rm min} \equiv \left[F/\left(1-P\right)\right]_{\rm min}^{\rm obs} = \int_{912\,{\rm \mathring{A}}}^{1000\,\mu{\rm m}} \tau_{\rm ext}(\lambda)/N_{\rm H}\,d\lambda / \left\{3\pi^2 \sum_{j=1}^{N}\sum_{\rm X} f_{{\rm X},j}\left([{\rm X/H}]_{\rm tot} - [{\rm X/H}]_{\rm gas}\right)\mu_{\rm X}/\rho_j\right\}$.

The SMC selective extinction toward the Sk 155 sightline is $E(B-V) \approx 0.09$ mag (Fitzpatrick 1985). From fitting the STIS Lyα data and the FUSE Lyβ data, D.E. Welty (2005, private communication) determined the HI column density to be $N_{\rm HI} \approx 2.51 \times 10^{21}\,{\rm cm^{-2}}$ for this region; he also estimated the H_2 column density from FUSE data to be $N_{\rm H_2} \approx 1.38 \times 10^{19}\,{\rm cm^{-2}}$. With a total-to-selective extinction ratio of $R_V \approx 2.1$, typical for the SMC wing where Sk 155 is located (Clayton et al. 2003), the visual extinction per H column for Sk 155 is $A_V/N_{\rm H} = R_V\,E(B-V)/\left(N_{\rm HI} + 2\,N_{\rm H_2}\right) \approx 7.44 \times 10^{-23}\,{\rm mag\,cm^2}$. For $912\,{\rm \mathring{A}} < \lambda < 3\,\mu{\rm m}$, we take the extinction curve typical for the SMC bar (Gordon & Clayton 1998) for Sk 155 since Preliminary analysis of the extinction toward Sk 155 appears that it is more similar to the "typical" SMC bar curve than to the curve for Sk 143 (D.E. Welty 2005, private communication); for $3\,\mu{\rm m} < \lambda < 1000\,\mu{\rm m}$ we adopt the theoretical $\tau_{\rm ext}(\lambda)/N_{\rm H}$ values calculated from the silicate-graphite-PAH model for the SMC bar which has been shown to successfully reproduce the observed extinction from the far-UV to mid-IR and the observed IR emission (Weingartner & Draine 2001, Li & Draine 2002). The integration of the extinction over the 912 Å–1000 μm wavelength range is approximately $\int_{912\,{\rm \mathring{A}}}^{1000\,\mu{\rm m}} \tau_{\rm ext}(\lambda)/N_{\rm H}\,d\lambda \approx 2.08 \times 10^{-26}\,{\rm cm^3/H}$.

If we know the total abundances $[{\rm X/H}]_{\rm tot}$ and gas-phase abundances $[{\rm X/H}]_{\rm gas}$ for the key dust-forming heavy elements, we can derive $f_{\rm obs}^{\rm min}$ from above through a general assumption of the constituent dust materials (e.g. silicates, amorphous carbon, magnesium oxides, or iron oxides) of the porous composite grain with a given porosity P, without any detailed knowledge of the dust sizes and shapes. On the other hand, for such a grain with a given porosity P and a given shape (e.g. prolate or oblate), we can calculate the theoretical values of $f_{\rm mod} \equiv \left[F/\left(1-P\right)\right]_{\rm mod}$ (see Purcell 1969, Li 2005). Apparently, for any valid grain models, the model-predicted $f_{\rm mod}$ should exceed $f_{\rm obs}^{\rm min}$. Below we examine the 2 possible grain models implied from the anomalous depletions suggested by Welty et al. (2001).

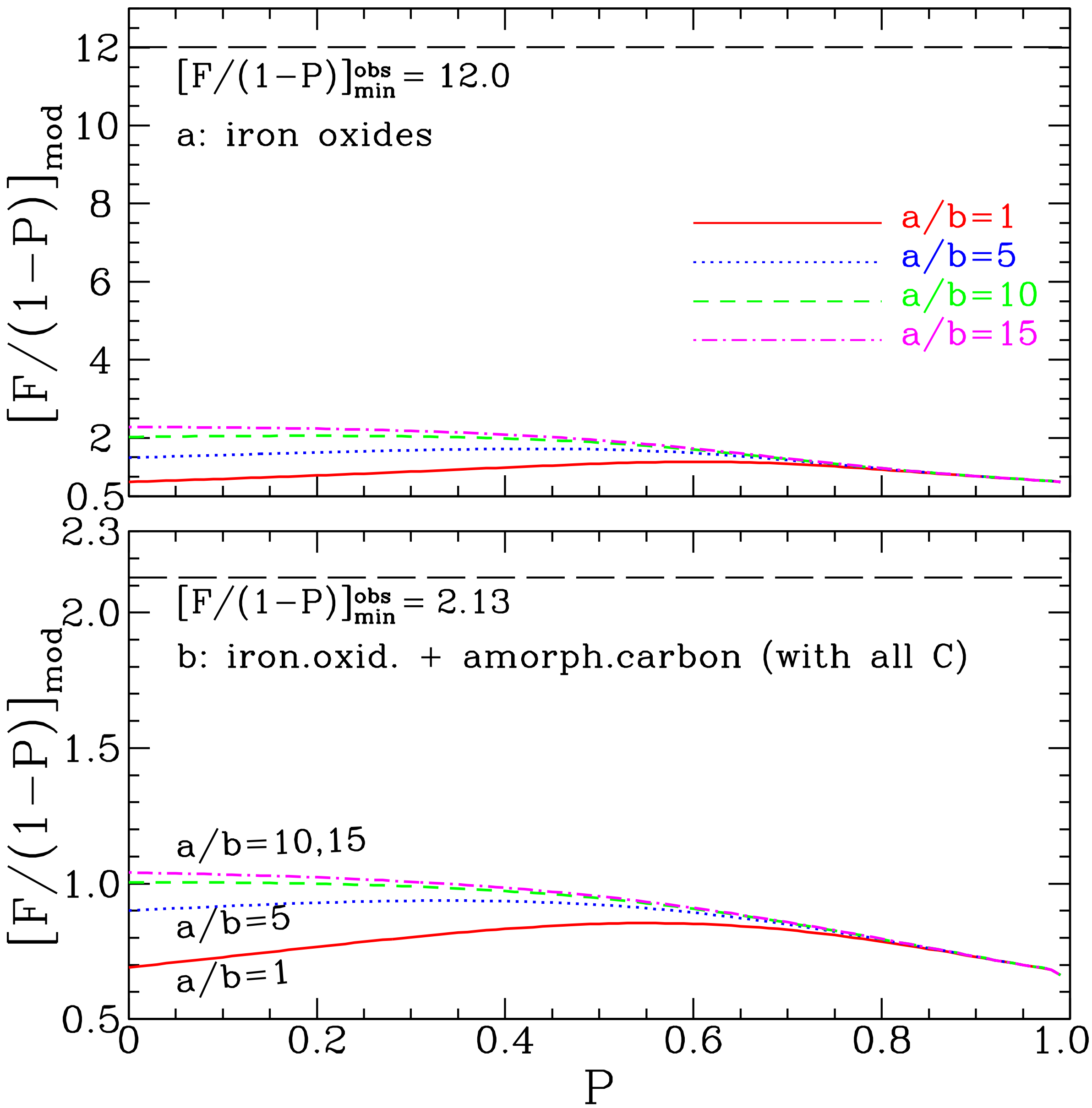

Fig. 1.— Model-predicted $f_{\rm mod} \equiv [F/(1-P)]_{\rm mod}$ as a function of porosity P for spherical (solid lines) or prolate porous composite grains consisting of (a) a mixture of iron oxides (FeO, Fe_2O_3, and Fe_3O_4), or (b) a mixture of FeO, Fe_2O_3, Fe_3O_4 and amorphous carbon with an elongation of $a/b = 5$ (dotted lines), $a/b = 10$ (dashed lines), and $a/b = 15$ (dot-dashed lines). The Fe and C abundances are taken to be solar scaled by Zn (Welty et al. 2001). The horizontal long-dashed lines plot the lower boundary $f_{\rm obs}^{\rm min} \equiv [F/(1-P)]_{\rm min}^{\rm obs}$ implied from the SMC extinction.

(1) *Metallic grains*? — Welty et al. (2001) suggested that metallic grains or iron oxides may dominate the dust populations in the SMC sightline toward Sk 155 since they thought that Si and Mg are essentially undepleted while Fe is severely depleted. If we take the abundances of heavy elements to be those of solar (Asplund, Grevesse, & Sauval 2005) scaled by the abundance of Zn ($[\mathrm{Zn/H}]_{\rm tot}^{\rm Sk\,155} \approx 0.004\,\mathrm{ppm}$; Welty et al. 2001) which is considered typically undepleted, the total iron abundance is $[\mathrm{Fe/H}]_{\rm tot}^{\rm Sk\,155} = [\mathrm{Zn/H}]_{\rm tot}^{\rm Sk\,155}[\mathrm{Fe/H}]_{\odot}/[\mathrm{Zn/H}]_{\odot} \approx 2.5\,\mathrm{ppm}$. For compact metallic iron grains ($P = 0$), this implies $f_{\rm obs}^{\rm min} \approx 24$. In order to have $f_{\rm mod} > 24$, these grains need to be highly elongated: with an elongation of at least ~ 25 for prolates and ~ 84 for oblates (see Fig. 3 of Li 2003b).[3] However, these needle-like iron grains would produce an extinction curve very different from that observed for the SMC since their extinction cross sections are essentially constant at wavelengths shorter than the long-wavelength cutoff and beyond which they decline as λ^{-2} (see Eqs.[3-5] of Li 2003a). Therefore, metallic iron grains are unlikely the dominant dust component in the SMC.

(2) *Iron oxides*? — Assuming that all 2.5 ppm Fe (relative to H) are evenly tied up in FeO, Fe_2O_3, and Fe_3O_4, porous grains consisting of FeO, Fe_2O_3, and Fe_3O_4 would have $f_{\rm obs}^{\rm min} \approx 12$. However, as shown in Figure 1a, the $f_{\rm mod}$ values predicted for the porous iron oxide dust are much smaller than $f_{\rm obs}^{\rm min}$ even for grains with an elongation as large as 15. Therefore, iron oxides are unlikely the dominant dust components in the SMC. Further more, even if we assume that (1) there is another major dust species – amorphous carbon,[4] (2) the total C abundance is that of solar scaled by the abundance of Zn (i.e. $[\mathrm{C/H}]_{\rm tot}^{\rm Sk\,155} = [\mathrm{Zn/H}]_{\rm tot}^{\rm Sk\,155}[\mathrm{C/H}]_{\odot}/[\mathrm{Zn/H}]_{\odot} \approx 24.5\,\mathrm{ppm}$), and (3) *all* C atoms are tied up in amorphous carbon grains, the model-predicted $f_{\rm mod}$ values are still much smaller than the lower-limit of $f_{\rm obs}^{\rm min} \approx 2.13$ (see Fig. 1b). Therefore, the extinction observed for the Sk 155 sightline is unlikely produced by a mixture of iron oxides and amorphous carbon.

3. Discussion

The anomalous depletions in the SMC sightline toward Sk 155 was derived by comparing the relative abundances [X/Zn] in the SMC with the corresponding patterns seen in the Galactic ISM, and assuming the relative total abundances of the SMC are not very different

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[3] We do not consider *porous* metallic needles since it is hard for us to believe that they could form and survive in the SMC.

[4] We do not consider graphite grains because if they are the dominant contributor to the SMC extinction, they need to be very small; but very small graphite grains would produce a strong 2175 Å extinction bump which is not commonly seen in the SMC.

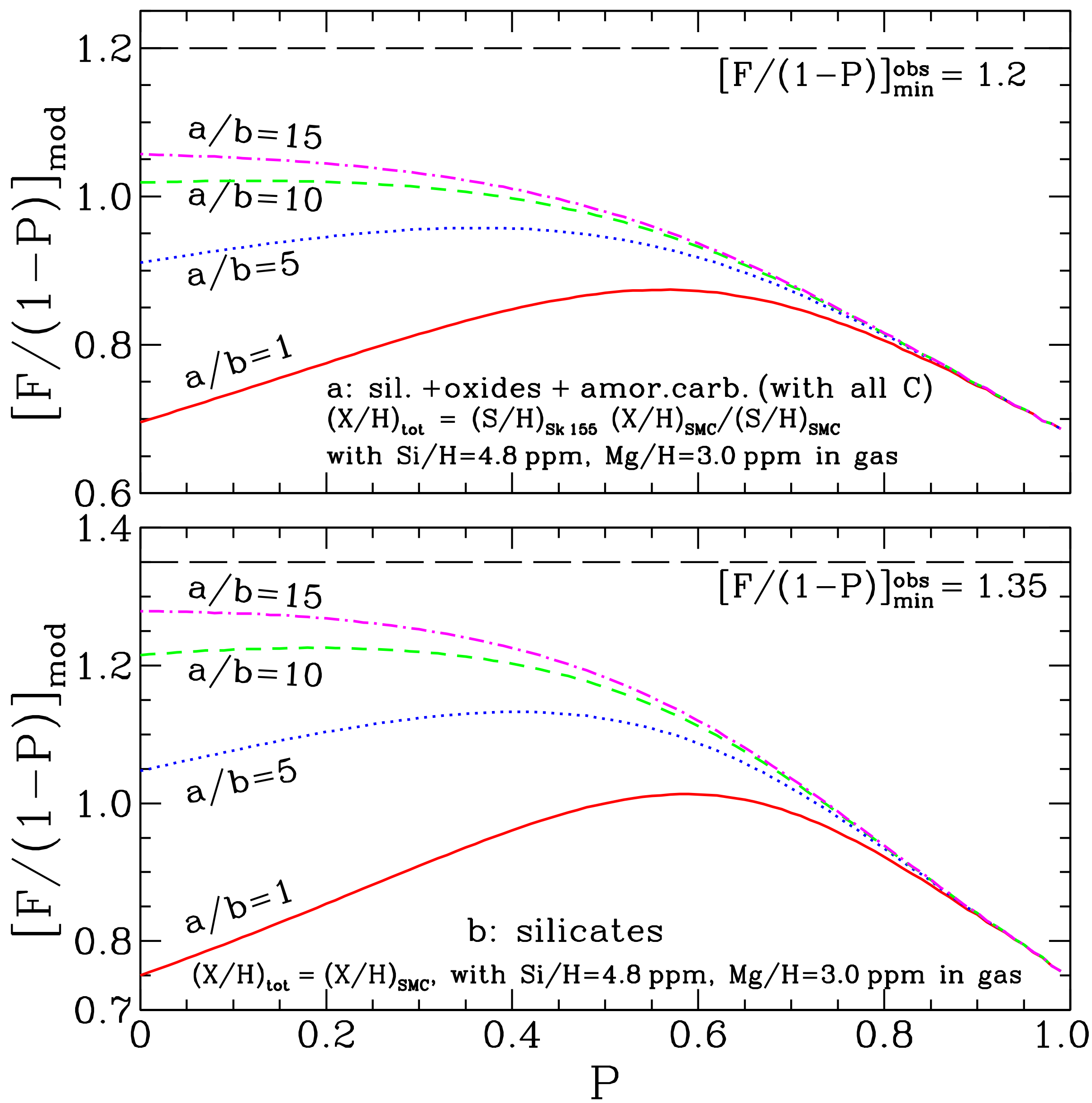

Fig. 2.— Same as Figure 1 but for (a) models consisting of a mixture of silicates, iron oxides, and amorphous carbon for which the total abundances are taken to be those of the RD92 SMC but scaled by the S abundance; and (b) models consisting of only silicate dust for which the RD92 SMC abundances are adopted as the total abundances. For both models, the Si and Mg gas-phase abundances of Welty et al. (2001) for Sk 155 are subtracted.

from those of solar (Welty et al. 2001). Vladilo (2002) argued that the SMC abundances may deviate from the solar ratios. Sofia et al. (2006) argued that Zn is not a suitable reference for comparison since Zn is modestly depleted in the Milky Way ISM; they further suggested that S may be a better comparison species since (1) S is essentially undepleted, and (2) both Si and S are formed through the same process (i.e. oxygen burning).

With S as the comparison species and adopting the solar abundances but scaled by the Sk 155 S abundance ($[\mathrm{S/H}]_{\mathrm{tot}}^{\mathrm{Sk\,155}} \approx 2.4\,\mathrm{ppm}$, Welty et al. 2001), we find that the available heavy elements are not sufficient to account for the observed extinction. One may argue that it is more appropriate to use the SMC abundances (Russell & Dopita 1992; hereafter RD92) as a reference rather than those of solar (i.e. assuming the abundances for the Sk 155 sightline to be those of the SMC scaled by S). In this case, the total abundances (relative to H) of the key dust-forming elements would be $\{\mathrm{Si, Mg, Fe, C}\} \approx \{6.6, 5.9, 4.3, 33\,\mathrm{ppm}\}$. Subtracting the gas-phase abundances of $\{\mathrm{Si, Mg, Fe}\} \approx \{4.8, 3.0, 0.35\,\mathrm{ppm}\}$ of Sk 155 (Welty et al. 2001), the abundances available for depletion are $\{\mathrm{Si, Mg, Fe}\} \approx \{1.8, 2.9, 3.9\,\mathrm{ppm}\}$. We assume that all the dust-phase Si atoms are incorporated into amorphous olivine $MgFeSiO_4$. This will also consume 1.8 ppm Mg and Fe. We take the remaining 1.1 ppm Mg to be depleted in MgO, and the remaining 2.1 ppm Fe evenly tied up in FeO, Fe_2O_3, and Fe_3O_4. We also assume that *all* the 33 ppm C are bound up in amorphous carbon. In so doing, we obtain $f_{\mathrm{obs}}^{\mathrm{min}} \approx 1.2$. However, as shown in Figure 2a, the model-predicted f_{mod} values never exceed $f_{\mathrm{obs}}^{\mathrm{min}}$ even for grains with rather large elongations. Therefore, the total abundances for Sk 155 are unlikely just the RD92 SMC abundances scaled by S.

If we simply adopt the RD92 SMC abundances as the total abundances for the Sk 155 sightline (i.e. without scaling down the SMC abundances), the dust-phase abundances would be $\{\mathrm{Si, Mg, Fe}\} \approx \{5.9, 6.6, 6.6\,\mathrm{ppm}\}$ after subtracting the gas-phase abundances of Welty et al. (2001). This depletion pattern roughly points to a composition of olivine silicates. As shown in Figure 2b, the f_{mod} values calculated from these silicate grains are still smaller than the observational lower boundary of $f_{\mathrm{obs}}^{\mathrm{min}} \approx 1.35$ even for grains with an elongation as large as 15.[5] This suggests that either the actual abundances for the heavy elements Mg, Si and Fe toward Sk 155 are higher than those of RD92, or alternatively, there must exist another dust component (e.g. amorphous carbon) which makes a considerable contribution to the extinction. For the latter case, with the addition of an amorphous carbon component which takes 2/3 of the total SMC C abundance (like the Milky Way diffuse ISM in which about 2/3 of the total C are depleted to form carbon dust; see Li 2005), the model-predicted

[5] With uncertainties as large as $\sim 20\%$ for A_V/N_{H}, silicate grains (together with oxides and/or amorphous carbon) with large elongations can account for the observed extinction (see Figs. 2a,b), but oxides (even together with amorphous carbon) are unable to do it (see Figs. 1a,b).

$f_{\rm mod}$ values exceed $f_{\rm obs}^{\rm min} \approx 0.77$ for grains of any shape and of a wide range of porosities (see Fig. 3a). This implies that grain models consisting of a mixture of silicate and carbon dust are capable of accounting for the SMC extinction.

The calculations discussed above all put a substantial fraction of Si and Mg in gas, as found for the Sk 155 sightline by Welty et al. (2001). Existing models for the SMC dust all assume a nearly complete depletion of Si, Mg and Fe into silicates. As shown in Figure 3b, the $f_{\rm mod}$ values calculated from silicates consuming all of the Si, Mg, and Fe elements (i.e. no gas-phase Si, Mg and Fe) of the RD92 SMC abundances exceed $f_{\rm obs}^{\rm min} \approx 0.99$ for grains with modest elongations and a wide range of porosities (the Sk 155 dust is expected to be elongated since an appreciable amount of polarization has been detected along the Sk 155 sightline; see Wayte 1990).[6] On the other hand, even if we assume that all the C elements are locked up in amorphous carbon, they alone are not able to account for the extinction since the model-predicted $f_{\rm mod}$ values are always smaller than $f_{\rm obs}^{\rm min} \approx 1.2$, suggesting that carbon dust can not be the dominant grain component in Sk 155.

4. Summary

By comparing the abundances of heavy elements relative to Zn in the SMC with the corresponding patterns seen in the Galactic ISM, and assuming the relative total abundances of the SMC are not very different from those of solar, Welty et al. (2001) derived the undepletion of Si and Mg and mild to severe depletions of Fe for the SMC star Sk 155. They further suggested that iron oxides and/or metallic grains, instead of silicates, may dominate the SMC dust, in marked contrast with current dust models for the SMC which all rely heavily on silicates. Based on the Kramers-Kronig relation, we study these anomalous depletions and their implications for our understanding of the SMC dust. It is found that neither iron oxides nor metallic grains (even with the addition of an amorphous carbon dust component) can account for the observed extinction. If using S as a reference and scaling either the solar abundances or the SMC abundances, the resulting abundances of the condensible elements are also insufficient to explain the observed extinction. However, we are able to account for the SMC extinction if adopting the SMC abundances and assuming all Si, Mg and Fe

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[6]Figure 3b shows that with the RD92 SMC abundances, *compact spherical* silicate grains are not able to account for the SMC extinction. The reason why Pei (1992) could fit the SMC extinction curve using such grains was because he adopted a higher Si abundance (higher than the RD92 SMC abundance by $\sim$30%). In the Weingartner & Draine (2001) model for the SMC, the extinction is also dominantly contributed by compact spherical silicate grains. This was also because they took a Si abundance $\sim$37% higher than that of RD92.

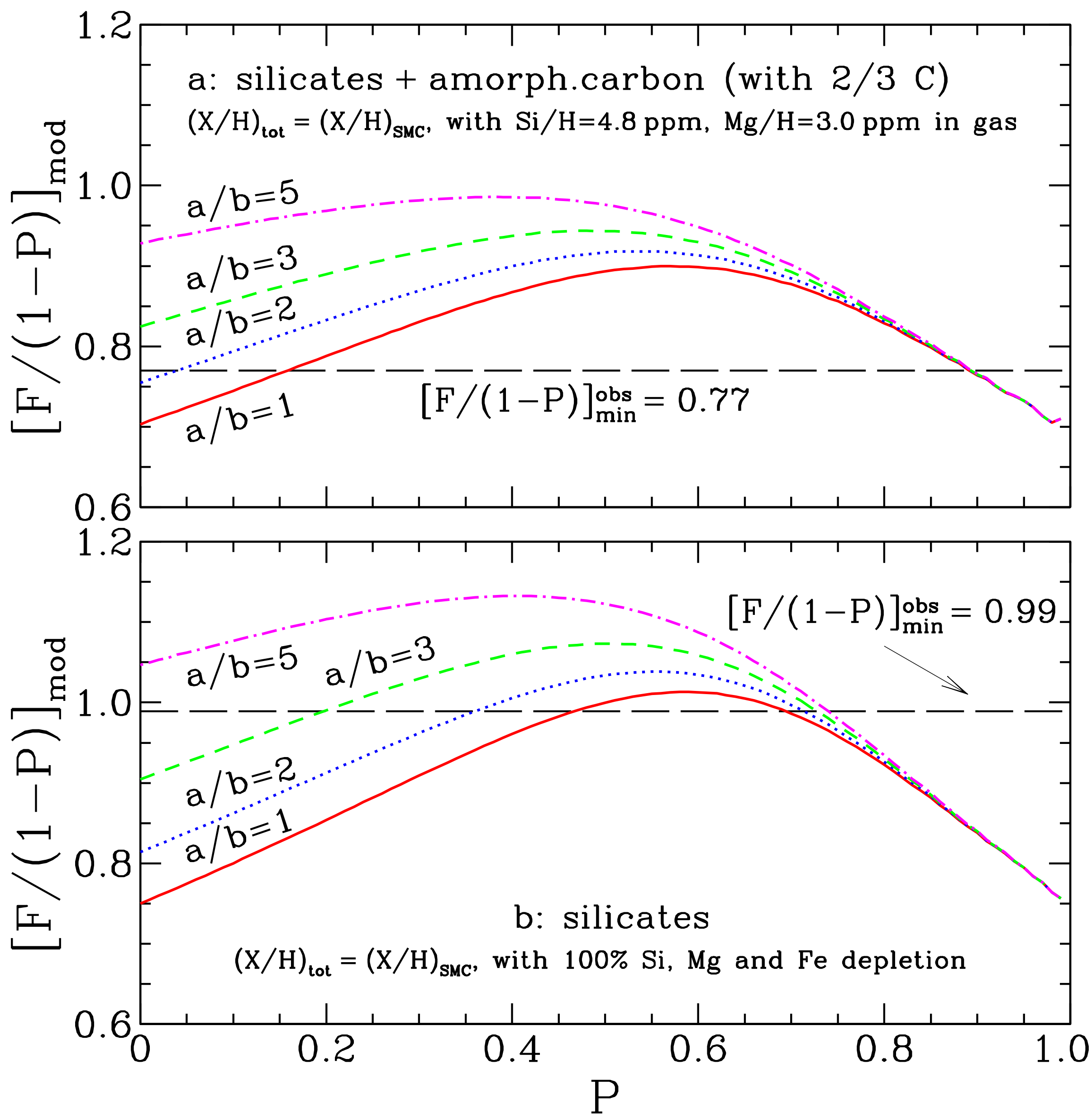

Fig. 3.— Same as Figure 1 but for (a) models consisting of a mixture of silicates and amorphous carbon (with a more modest elongation) for which the total abundances are taken to be those of the RD92 SMC with the Si and Mg gas-phase abundances of Welty et al. (2001) subtracted and with 2/3 of the total C locked up in amorphous carbon; and (b) models consisting of only silicates for which the dust-phase Si, Mg and Fe abundances are taken to be those of the RD92 SMC abundances (i.e. assuming 100% depletions of Si, Mg and Fe).

elements are locked up in silicates or a combination of a partial depletion of these elements in silicates and a partial depletion of C in amorphous carbon. In both cases, silicates are a major contributor to the SMC extinction.

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